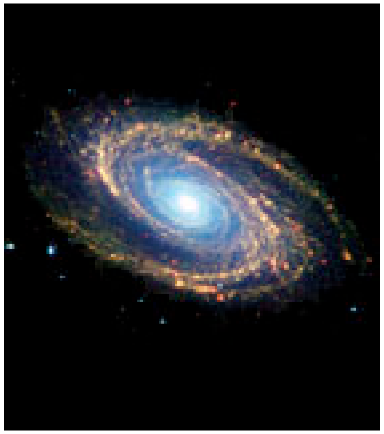
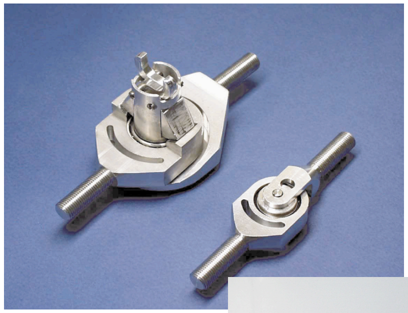
Structural Technology for Large Cryogenic Apertures

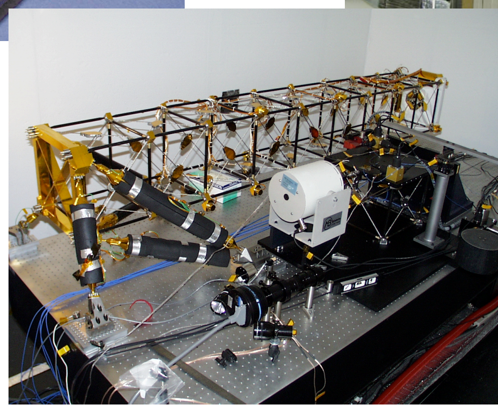


Prof. Lee D. Peterson
Dr. Jason D. Hinkle
University of Colorado

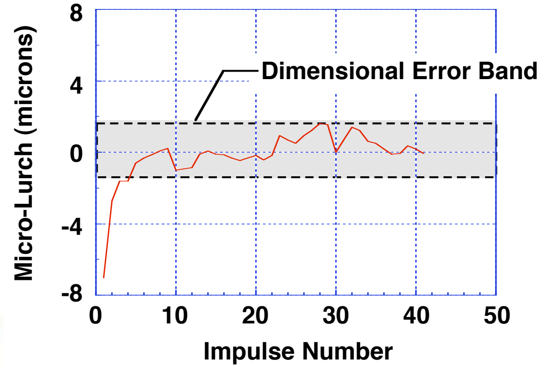
Presented at
From Spitzer to Herschel and Beyond
Pasadena, California
9 June 2004

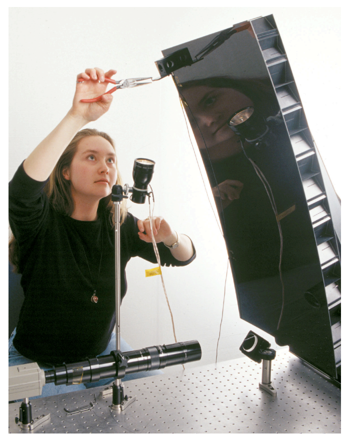
Some Background, History and Perspective

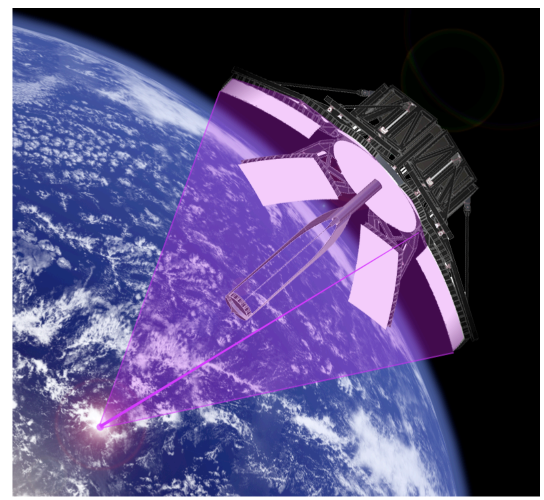




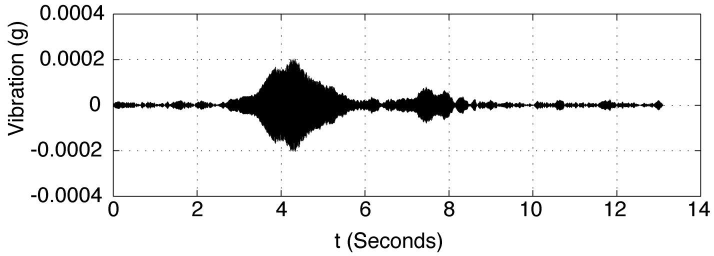
Micro-Lurch







Microdynamics



MADE

Structural Models at Nanometer Scale

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Presentation Objectives

- To enable Large Space Telescopes ….
  - ***How will large space structure requirements scale with observatory size?***
  - ***How can these requirements be met?***
- Conclusions
  - Apply rational methodology for large space structure requirements allocation (independent of architecture)
  - Generalized scaling laws allow "JWST-6 meter technology" to be extrapolated to "Beyond Spitzer-10 meter technology"
  - E.g.

    Need ~8 times the wavefront control, or …

    Need ~8 times the material rigidity, or …

    Need ~8 times the vibration isolation and/or structural control, or …

    Need ~3 times the deployed structural depth

Principal Observations and Conclusions

- **What we know …**

Structural depth will strongly affect the the stability of any large space telescope. Deployed depth for optical precision therefore remains a key technical challenge.

- **What we think we know …**

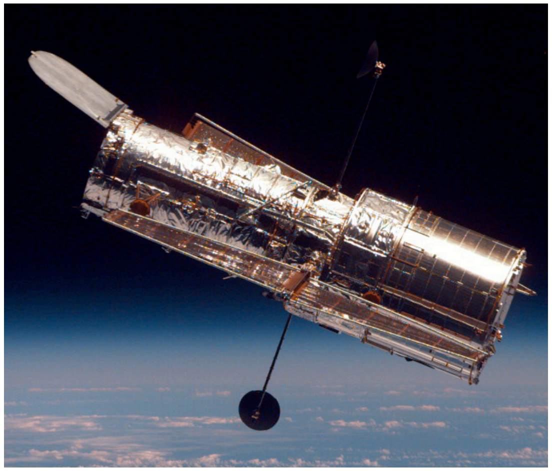
System-wide static, dynamic, and microdynamic stability should be achieved through balanced passive structural performance and active structural/wavefront control.

- **What we think …**

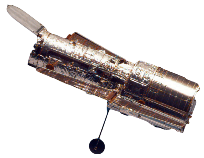
10-meter class telescopes would be made structurally feasible today, with conceivable advancements in technology, while 30-meter class (and above) are (probably) substantial challenges.

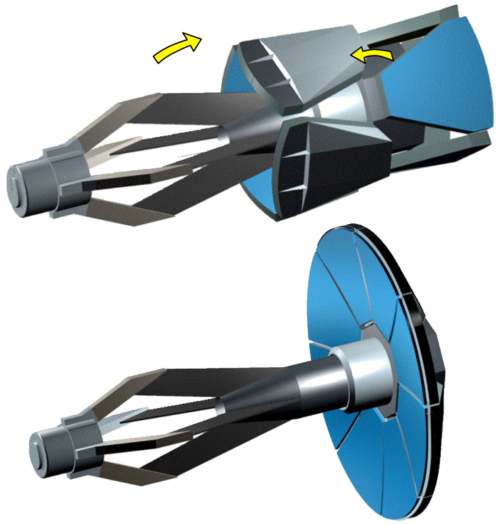
Large Space Telescopes Challenge Structures, Dynamics and Controls Technology

Today



Tomorrow





- 3-10 x diameter (or more)
- <1%-10% areal density (or less)

Goodrich Concept

Potential for 100 to >1000 times (or more) less structural rigidity

"Deal with phenomena as primary criteria which have been considered as only secondary in the past."
-J.M. Hedgepeth, (1981) NASA CR 3484

Scaling Analysis Provides a Rationale Basis for Defining Technological Benchmarks

- As telescope size increases …

  Will existing design concepts still work?

  What is the effect of material choice?

  Will more vibration isolation and active control be needed?

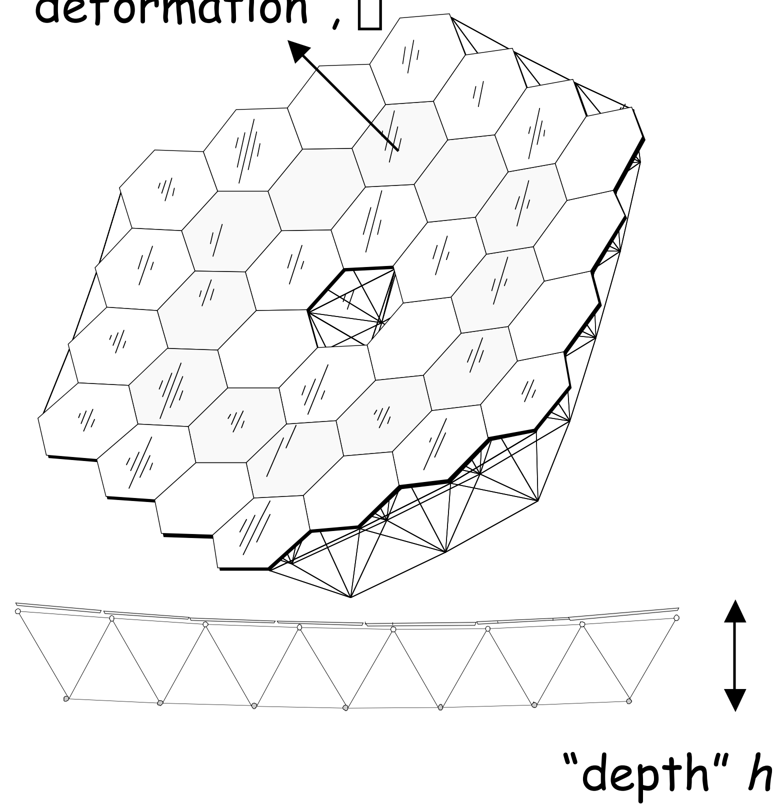
  How much more wavefront control will be needed?

  What are the impacts on integration and test?

- Principal structural trade is deployed structural volume (depth) vs structural stiffness

  For example, modest increases in deployed volume just as beneficial as the use of carbon nanotubes

How Structural Requirements Scale with Size and Architecture



- Consider
  - Deformation under inertial loading
  - Deformation under dynamic loading
  - Microdynamics
  - Effect of mechanical tolerances
  - Structural depth, mass fraction, material specific stiffness
- Conclusions
  - Vibration frequency is an indicator of structural performance
  - Depth is directly linked to frequency
  - Deformation increases with size^4, but decreases with depth^2
  - Frequency, damping and microdynamic stability can be effectively traded to determine candidate designs

Rational Methodology for Large Space Structure Requirements Allocation and Conceptual Design

- Literature ~1980 defined Large Space Structure design

  Hedgepeth, "Critical Requirements for the Design of Large Space Structures" NASA CR-3484, 1981

  Hedgepeth, "Support Structures for Large Infrared Telescopes" NASA CR-3800, 1984

  Hedgepeth, Mikulas and MacNeal "Practical Design of Low-Cost Large Space Structures" Astronautics and Aeronautics, 1978

  Mikulas, "Structural Efficiency of Long and Lightly Loaded Truss and Isogrid Columns for Space Applications" NASA TM-78687, 1978

- Recent developments

  Lake, Peterson, Levine, "A Rationale for Defining Structural Requirements for Large Space Telescopes" J. Space. Rockets, 2002

  Peterson, Hinkle, "Microdynamic Design Requirements for Large Space Structures" AIAA-2003-1451, 2003

Availabel at http://sdcl.colorado.edu

Specification of a Large Space Structure Design Problem

> *"The rational design of all structures must start with the definition of the task or the function of the structure."*
> *-J.M. Hedgepeth, (1981) NASA CR 3484*

- What is the nominal required configuration and shape?
  - Optical prescription
- What are the loads?
  - Mechanical loads
  - Thermal gradients
  - Operational concept

    Launch, deployment, commissioning
    Cryogenics
  - Orbital influences

    Thermal, gravity gradient,
    ground point tracking
- What are the geometric stability requirements?
  - Spatial nature of dimensional tolerances
  - Temporal nature of dimensional tolerances

Deformation of a Telescope Mirror due to On-Orbit Disturbance Loads

- The disturbance loads that can deform a telescope mirror include: thermal; inertial (quasi-static); and on-board (harmonic dynamic).

- An upper bound on the RMS deformation due to inertial loads scales like:

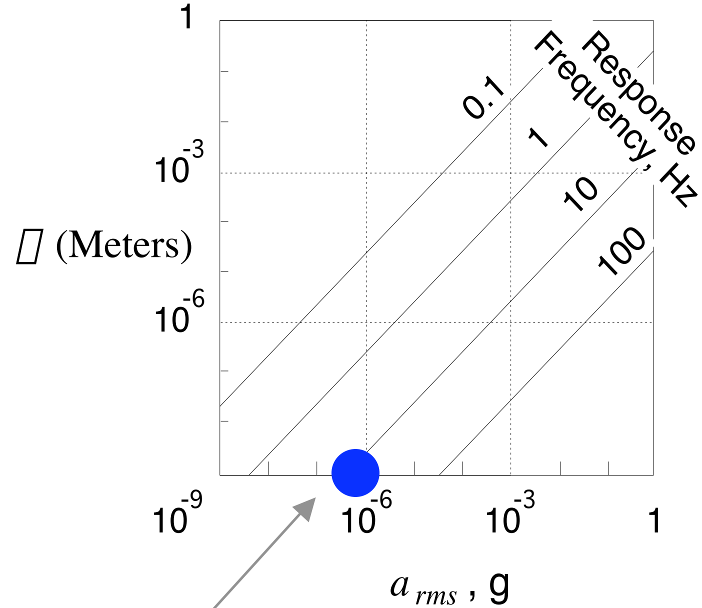
$$\delta \approx \frac{a_{rms}}{4\pi^2 f_0^2}$$

RMS Deformation

Lowest Modal Frequency

- An upper bound on the RMS deformation due to on-board harmonic loads scales like:

$$\delta \approx \left(\frac{1}{2\zeta}\right)\frac{a_{rms}}{4\pi^2 f_0^2}$$



10 Hz: "Micro-gee & Nanometer"

How Does Mechanical Deformation Scale?

- Quasi-Static (Solar Photon Pressure)

"Dimension"

RMS Deformation

$$\delta \approx \frac{p_{solar} A}{4\pi^2 M f_0^2} \Rightarrow \propto \frac{D^2}{f_0^2}$$

Lowest Modal Frequency

- Transient (Slew and Settle)

$$\delta = c_0 \frac{D\theta}{T_{Slew}^2} \cdot \frac{1}{\pi^2 f_0^2} e^{-2\pi\zeta f_0 T_{Settle}} \Rightarrow \propto \frac{D\theta}{\left(T_{Slew} f_0\right)^2}$$

Peak or RMS Deformation

- Resonant (Reaction Wheel Actuator)

$$\delta = c_0 \frac{1}{1 + f_0^2 / f_c^2} \cdot \frac{C_1}{2\sqrt{2}\pi^2 M\zeta} \Rightarrow \propto \frac{f_c^2}{f_0^2} \cdot \frac{C_1}{M\zeta}$$

Isolator Frequency

Modal Damping Ratio

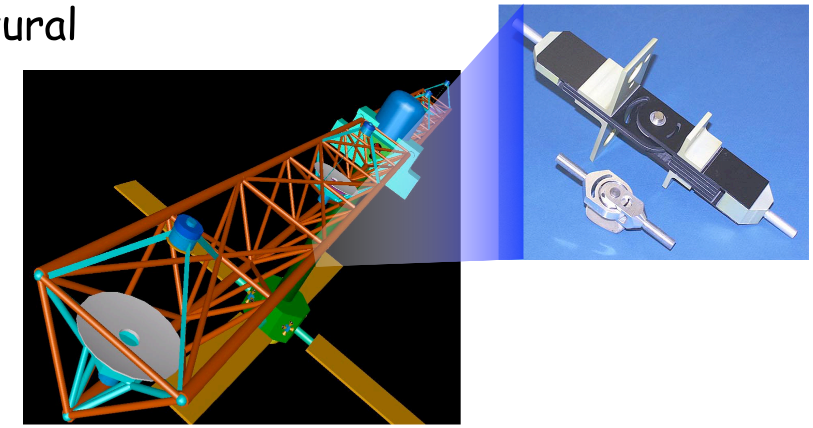
Microdynamics can be Bounded in a Similar Manner for Purpose of Design

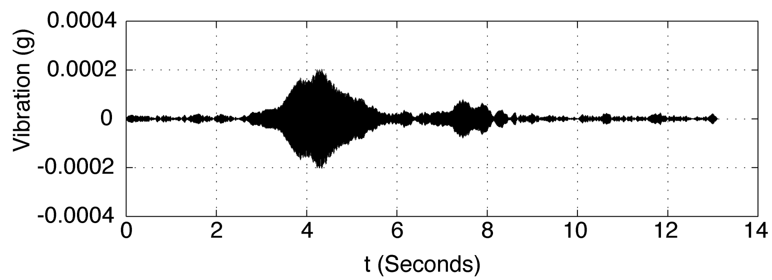
- "Microdynamics": Variety of nonlinear structural mechanical and material effects
    - Friction below 10 micron displacement

      Microslip

      Interface instability
    - Material anelasticity below 10 μ-strain

      Microyield
- Bound for "nanoquakes:





Microdynamic amplification factor (typically 1-5?)

Global frictional loss factor

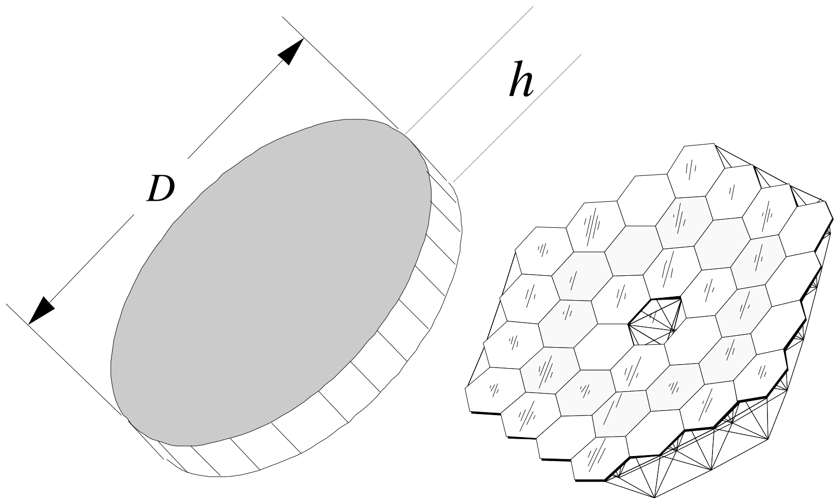
$$\boxed{\square_{microD} \, \square \, \frac{\square_{microD}}{4} \square \square}$$

Previous deformation peak (static or dynamic)

Peterson, L.D. and Hinkle, J.D. "Microdynamic Design Requirements for Large Space Structures", AIAA-2003-1451, Proceedings of the 44th Structures, Structural Dynamics and Materials Conference , Norfolk, Virginia, April, 2003

How Does Vibration Frequency Scale?
Case 1: Filled Aperture - Reaction Structure

- Structurally represents JWST deployed mirror or assembled segmented mirror



Equivalent Sandwich Plate   Reflector System

Lake, Peterson, Levine, 2001

Material Specific Modulus

Depth

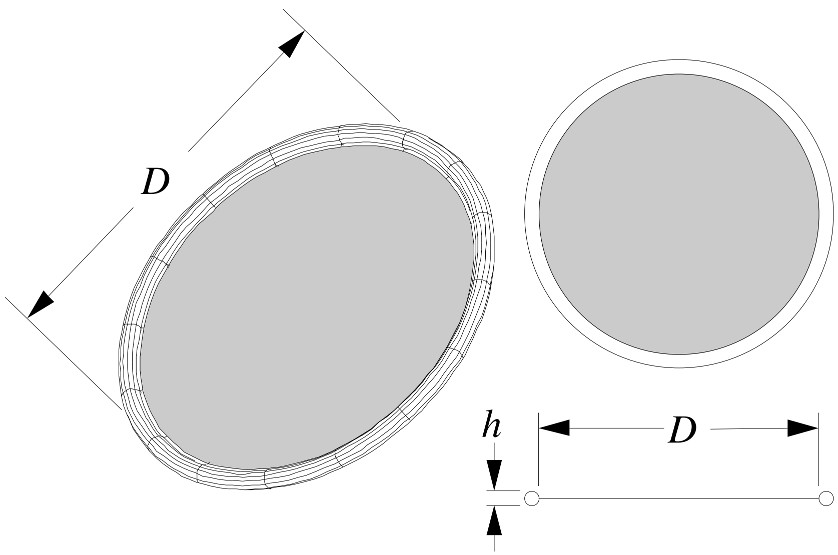
$$f_0 = 0.852\frac{h}{D^2}\sqrt{\frac{E}{\rho}}\sqrt{\eta}$$

$$\eta = \frac{m_{structure}}{m_{structure} + m_{mirror}} \leq 1$$

Note that areal density is hidden in the "structural mass fraction"

How Does Modal Frequency Scale?
Case 2: Filled Aperture - Tensioned Membrane

- Stiffness derived from tension of optical membrane
- Compression ring structure provides tension
    - Assume membrane mode is lowest mode



Oblique View
Reflector Dimensions

Lake, Peterson, Levine, 2001

Buckling stress ratio

$$f_0 = 0.574\,\frac{h}{D^2}\sqrt{\frac{E}{\square}}\sqrt{\frac{\square}{1\square\square}}\sqrt{\square}$$

Case N: Frequency Scaling for More General Cases

- Rely on Buckingham Pi Theorem
  - Infer functional dependencies from numerical examples (e.g., Adler and Mikulas, 2003)

$$f_n = \frac{h}{D^2}\sqrt{\frac{E}{\square}} \cdot g(\square, n) \cdot r(\square, \square, \square)$$

Structural Mass Fraction

Geometric Nondimensional Scale Factors (Problem Dependent)

How Structural Deformation Scales

- For many dynamic and quasi-static loads

$$\square \quad \frac{1}{f_0^2} P$$

Load influence function

Lowest mode

- For representative configurations

Structural depth

$$f_0 \; \mu \; \frac{h}{D^2} \sqrt{\frac{E}{\square}} \sqrt{\square}$$

Structural mass fraction

Specific modulus

Size/Diameter

- Deformation scales as:

$$\boxed{\square \mu \; \frac{D^4}{h^2} \cdot \frac{1}{E/\square} \cdot \frac{1}{\square} \cdot P}$$

Application to Notional 50-m NASA Terrestrial Planet Finder Interferometer

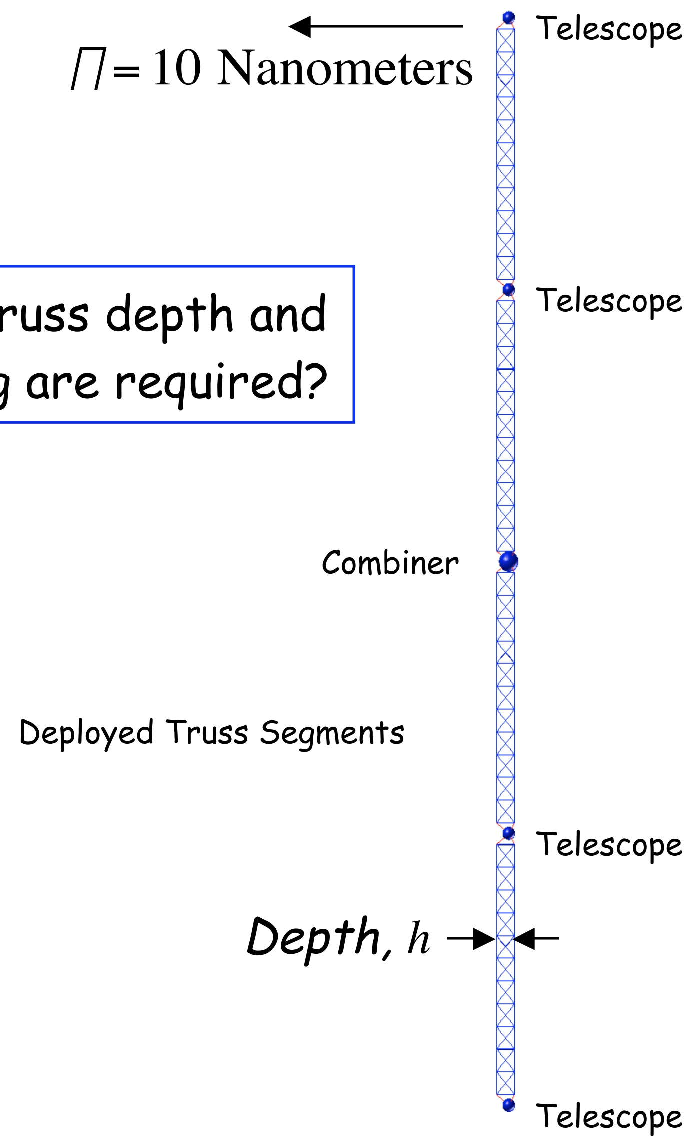
- Geometric configuration and constraints
  - 1000 kg spacecraft, 4 x 250 kg telescopes
  - 10% structural mass fraction
  - 3-longeron truss
- Stability requirement
  - 10 nm @ tip
- Loads
  - Reaction Wheel Actuators (RWA)

    Tetrahedra @ 0.3 N-m saturation torque

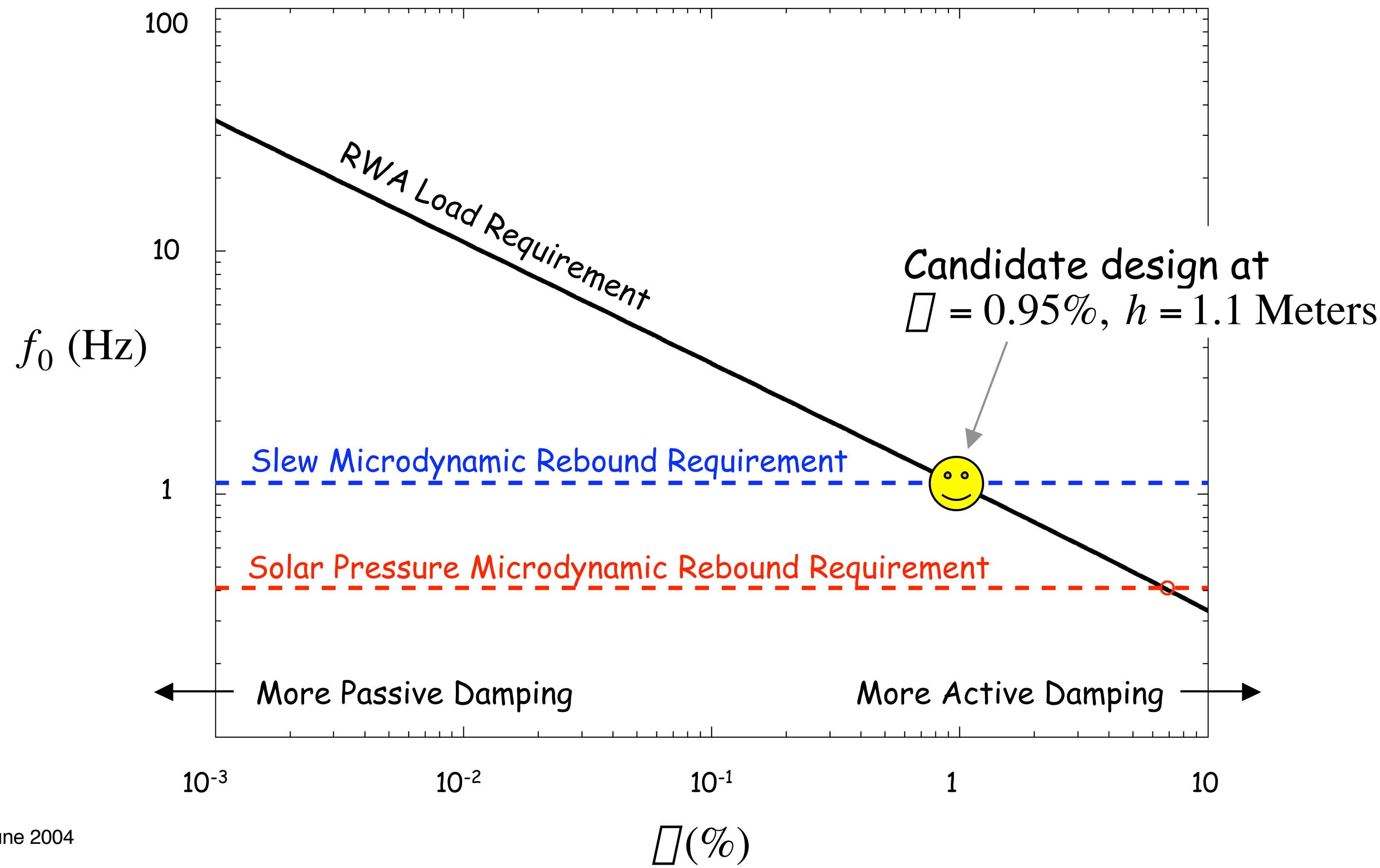
    0.4 gm-cm static unbalance

    0.1 Hz second order isolation
  - Slew
  - Solar Photon Acceleration
- Global hysteresis due to friction
  - 1%, with microdynamic amplification factor of 5:1

What truss depth and damping are required?



Dynamic Loads Analysis Demonstrates Trade among Frequency, Depth, Microdynamics and Passive/Active Damping



Scaling Reveals Key Trades in Structural Architecture

- Use parameterized design scaling analysis

$$\boxed{\square\mu \frac{D^4}{h^2}\cdot\frac{1}{E/\square}\cdot\frac{1}{\square}\cdot P}$$

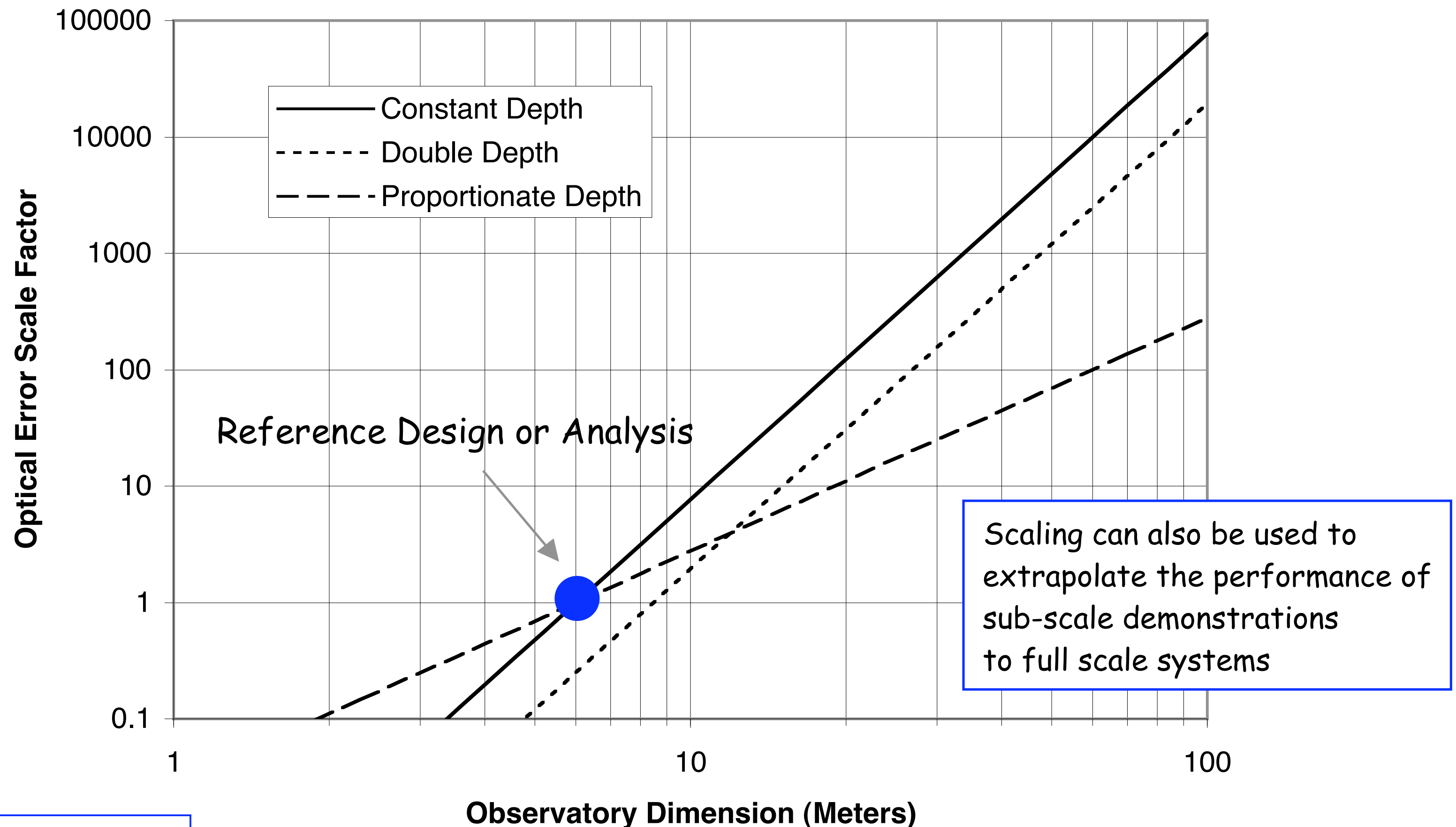
- Examples:
  - Tripling depth *h* has same effect as 10:1 improvement in material properties

    Same impact as "bulk carbon nanotube modulus" breakthrough
  - Change *D*, then *h* that varies like D^2 has same stability

    Unless load P depends on D
  - Increasing structural mass fraction can also compensate for other parameters

    But always < 1
  - Reducing load intensity (e.g. through better isolation) by factor of 10:1 can reduce required structural depth by a factor of $10^{(1/2)}$

Scaling Can Extrapolate Known Performance to Future Dimensions



$$\square \mu \frac{D^4}{h^2} \cdot \frac{1}{E/\square} \cdot \frac{1}{\square} \cdot P$$

Technology leading to increased deployed structural depth will have a substantial impact on deployed telescope performance.

Comparison of Designs with the Same Structural Mirror Stability

Diameter	Depth	Material Modulus	Wavefront Control	Load Factor
6 Meters	1:1	1:1	1:1	1:1
10 Meters	2.8:1	1:1	1:1	1:1
10 Meters	1:1	7.7:1	1:1	1:1
10 Meters	1:1	1:1	7.7:1	1:1
10 Meters	1:1	1:1	1:1	7.7:1

Deployed depth

Better than carbon nanotubes (at 4K!)

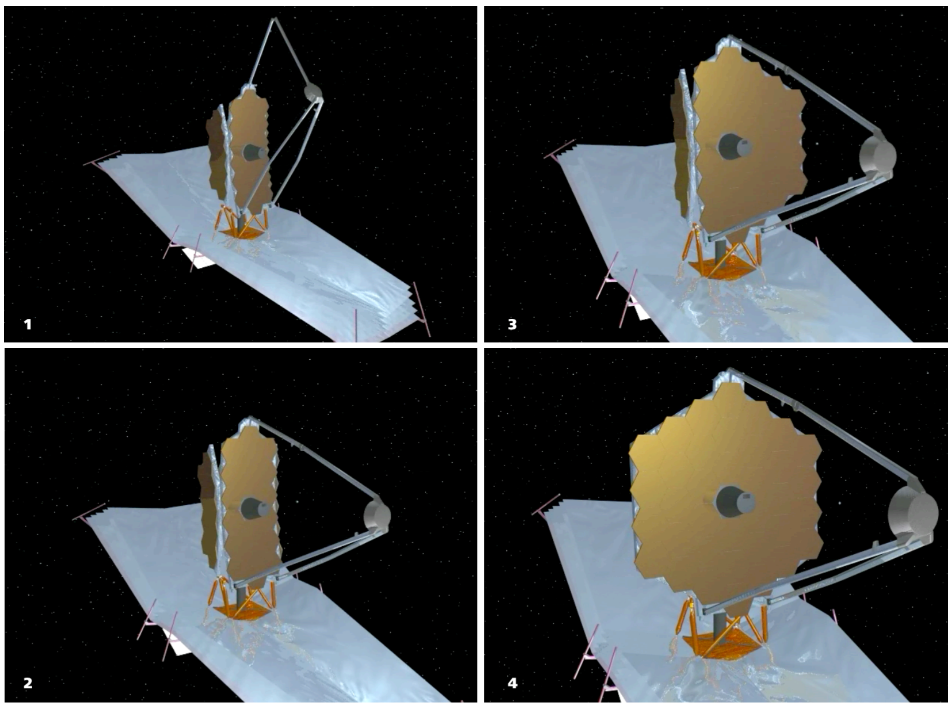
Dynamic, not static

Active vibration damping and/or active control

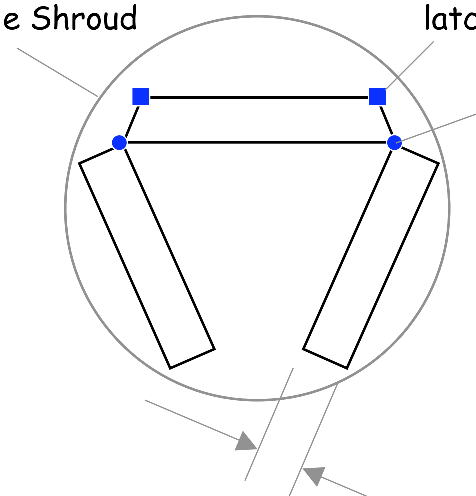
Advancements in all these areas will benefit the mission

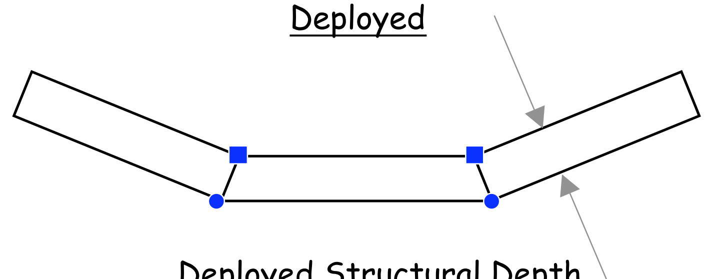
JWST Mirror Folding Scheme with Fixed Structural Depth

JWST Mirror Deployment



http://jwstsite.stsci.edu/gallery/deploy_graphics/lg_mirror_deploy.tif (2003-09-09)

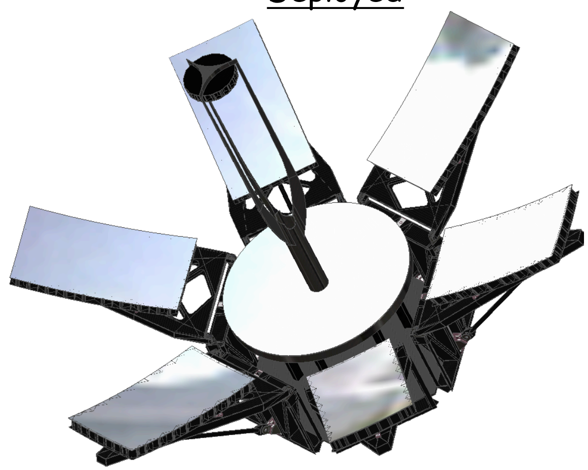


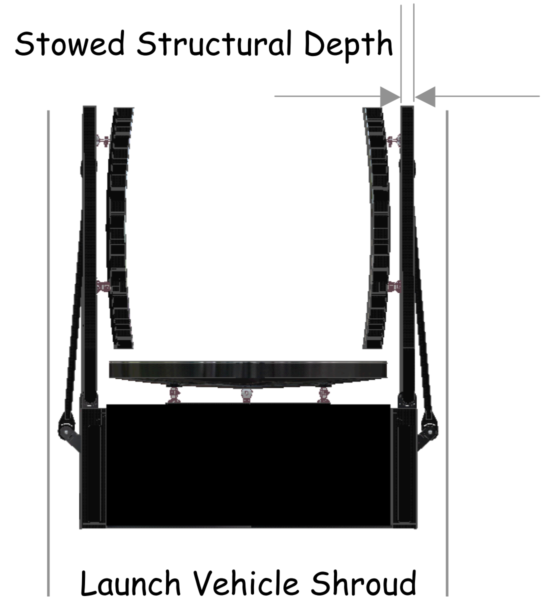


Deployable Lidar Telescope Folding Scheme with 7:1 Deployed Structural Depth

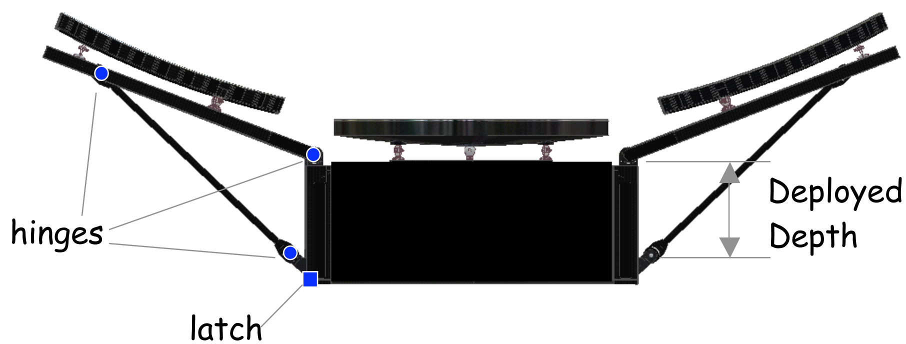
Stowed

Deployed





- Concept (and hardware) developed by NASA Langley and Composite Optics (now ATK-COI) under SBIR ~1998 (Lake et al, 1999)



Key to deployed depth: More degrees of freedom ⟶ More articulation

Comments and Caveats

- Applicability of the scaling analysis
  - Primarily applies to dynamic loads

    Thermal loads analysis leads to a similar scaling analysis
  - Applies to different structural shapes

    Booms, plates, tensioned membranes, compression columns (with some modifications)
- Caveats
  - Analysis assumes structure is a "large space structure" designed considering its loads environment
  - Other factors can also add to the structural mass

    Ground test

    Minimum gauge materials

    Fabrication effects

Summary and Conclusions

- As space telescopes become larger and lighter, their stiffnesses will be lower and their sensitivity to disturbances will increase substantially.
  - Deployed depth is a key technology to achieving satisfactory stiffness, especially at larger telescope dimensions
- Active figure- and wavefront-control systems are also required

  Optimum system designs will "spread the pain" between passive structural stiffness and active control.

- Technology benchmarks can be established using the scaling analysis described above
- Extrapolation of JWST-like (6-meter) technology to Beyond-Spitzer (10-meter) requirements
  - Technical development goals identified for various system technologies

References

- Available from http://sdcl.colorado.edu/Publications

  - Lake, M.S., Peterson, L. D. and Levine, M.B., "A Rationale for Defining Structural Requirements for Large Space Telescopes" AIAA-2001-1685. *Proceedings of the 42nd Structures, Structural Dynamics and Materials Conference* , Seattle, Washington, April, 2001. (Also *J. Spacecraft and Rockets*, Vol. 39, No. 5, September-October 2002, pp 674-681.)
  - Peterson, L.D. and Hinkle, J.D. “Implications of Structural Design Requirements for Selection of Future Space Telescope Architectures” SPIE-5066-05, *Proceedings of the SPIE Annual Meeting*, San Diego, California, August, 2003.